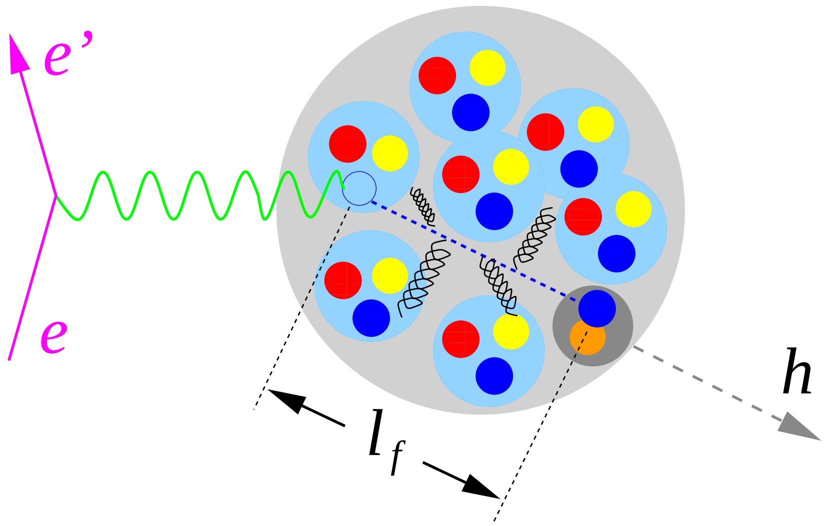
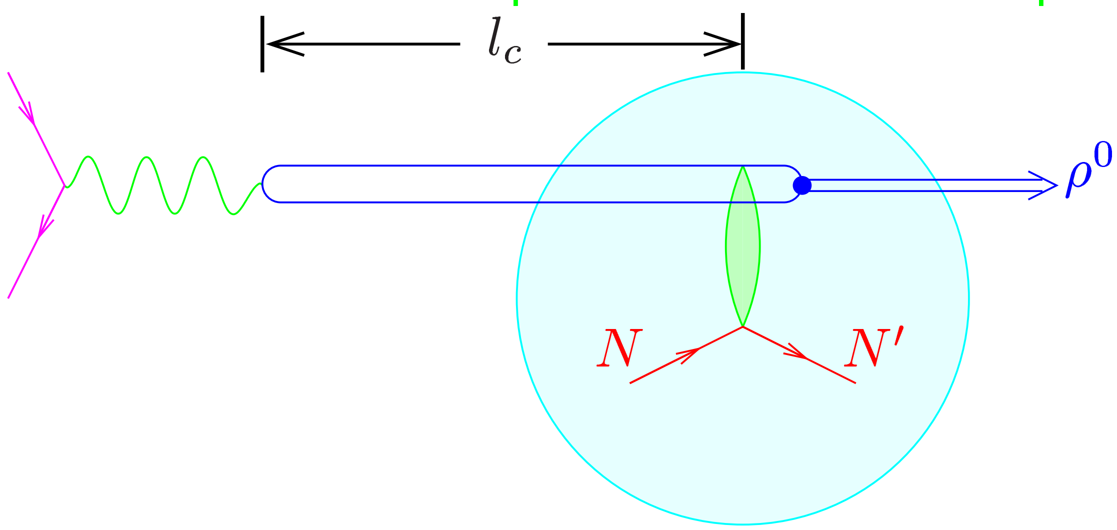
Evolution of Virtual Quantum States

T. G. O'Neill, ANL (for the HERMES collaboration)

- Perturbing medium ⇒ probe lifetime and interactions of virtual quantum states mediating a reaction.
- Dedicated HERMES N_2 runs ⇒ nuclear medium
- Hadronization of struck quarks in Deep Inelastic Scattering events



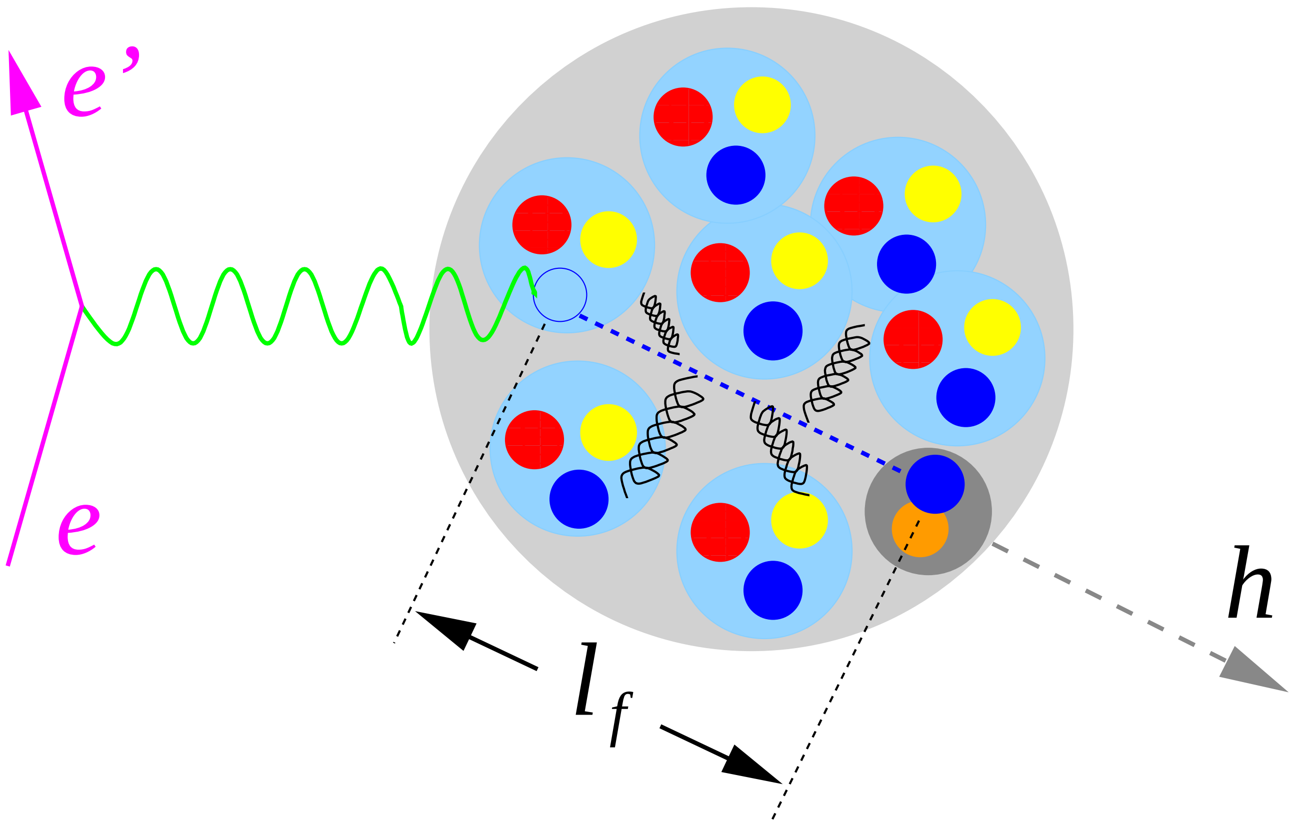
- Initial State Interactions of photon's hadronic components



  - Total σ for $\gamma^* A$ and γA
  - Exclusive ρ^0 production: l_c well-determined
- Virtual particles "real" ⇒ easy to interpret experiments
- WARNING: $\hbar = c = 1$

hermes

Nuclear Attenuation of DIS Hadrons



Attenuation in nucleus (divide by DIS σ to cancel shadowing):

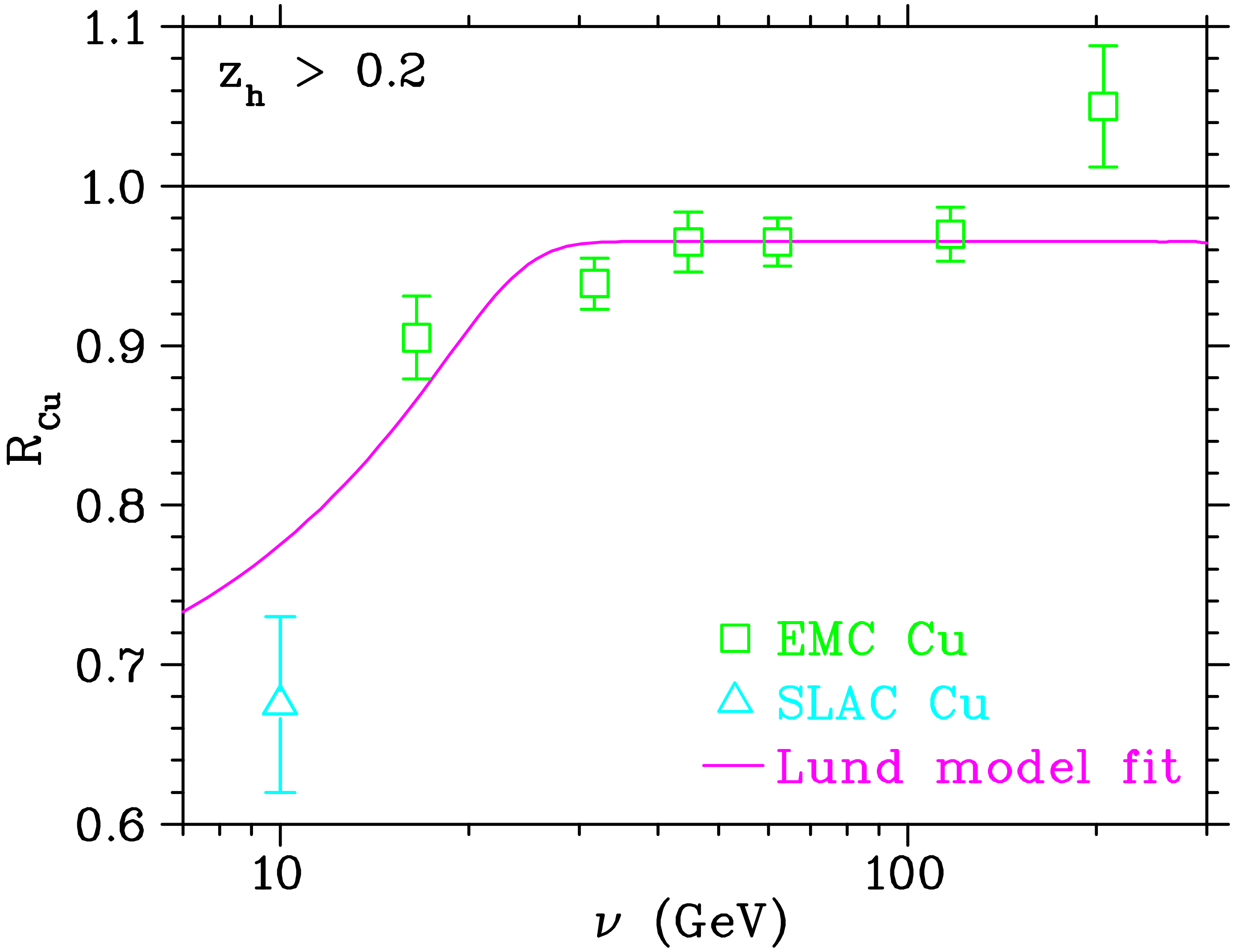
$$R_A(z_h,\nu) = \frac{\left.\frac{1}{\sigma}\frac{d^2\sigma}{dz_h d\nu}\right|_A}{\left.\frac{1}{\sigma}\frac{d^2\sigma}{dz_h d\nu}\right|_D} = \frac{\left.\frac{1}{N_e}\frac{d^2 N_h}{dz_h d\nu}\right|_A}{\left.\frac{1}{N_e}\frac{d^2 N_h}{dz_h d\nu}\right|_D}$$

Can't calculate Feynman amplitude directly, need model using interactions of virtual particles. In simple model hadron results from decay of unstable quark [A. Białas and T. Chmaj, PLB **133** (1983) 241]:

$$l_f = \frac{E_q}{m_q}\tau_q = \frac{\nu}{m_q}\tau_q.$$

If $\sigma_{qN} \neq \sigma_{hN}$, R_A depends on ν.

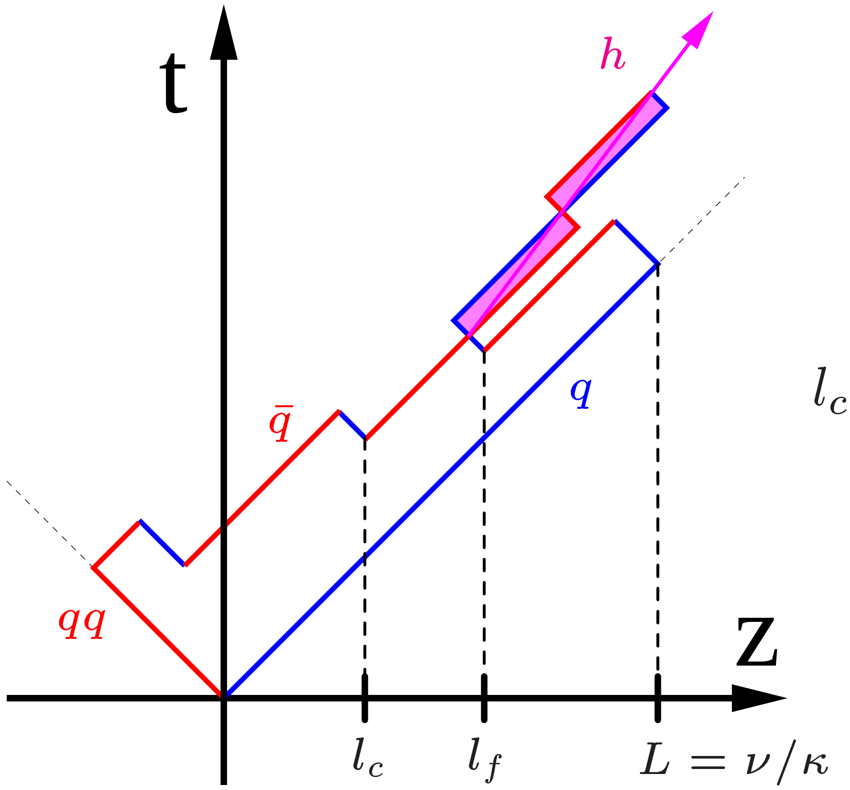
Early Data: Hadronization in Copper



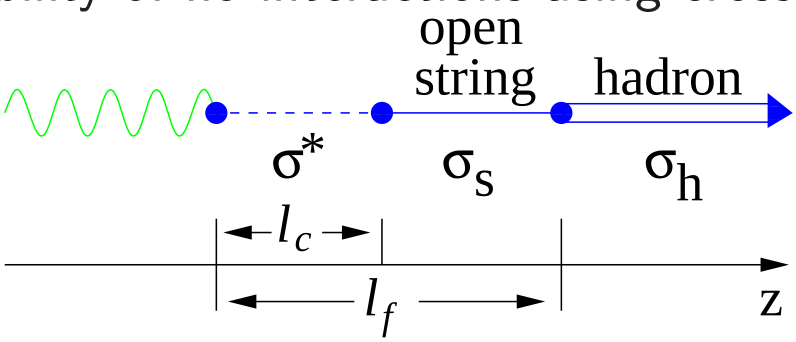
- SLAC ^{1,2}H, Be, C, Cu, Sn $eN \to eh^{\pm}Y$, $E = 20.5$ GeV
  [L.S. Osborne *et al.*, PRL **40** (1978) 1624]
- CERN EMC ^{2}H, C, Cu, Sn $\mu N \to \mu h^{\pm}Y$,
  $E = 100, 120, 200, 280$ GeV [J. Ashman *et al.*, ZPC **52** (1991) 1]
- Data suggest $\sigma_q < \sigma_h$
- More realistic Lund-based model [A. Białas and M. Gyulassy, Nucl. Phys. B **291** (1987) 793]
  - Lund distributions of l_c, l_f; $\sigma_h = 20$ mb fixed
  - "Fit": $\sigma^* = 0.75$ mb, $\sigma_s = 20$ mb, $\kappa \approx 1$ GeV/fm

More Realistic Models

- Lab frame fragmentation of q and qq in Lund model [A. Białas and M. Gyulassy, Nucl. Phys. B **291** (1987) 793]:

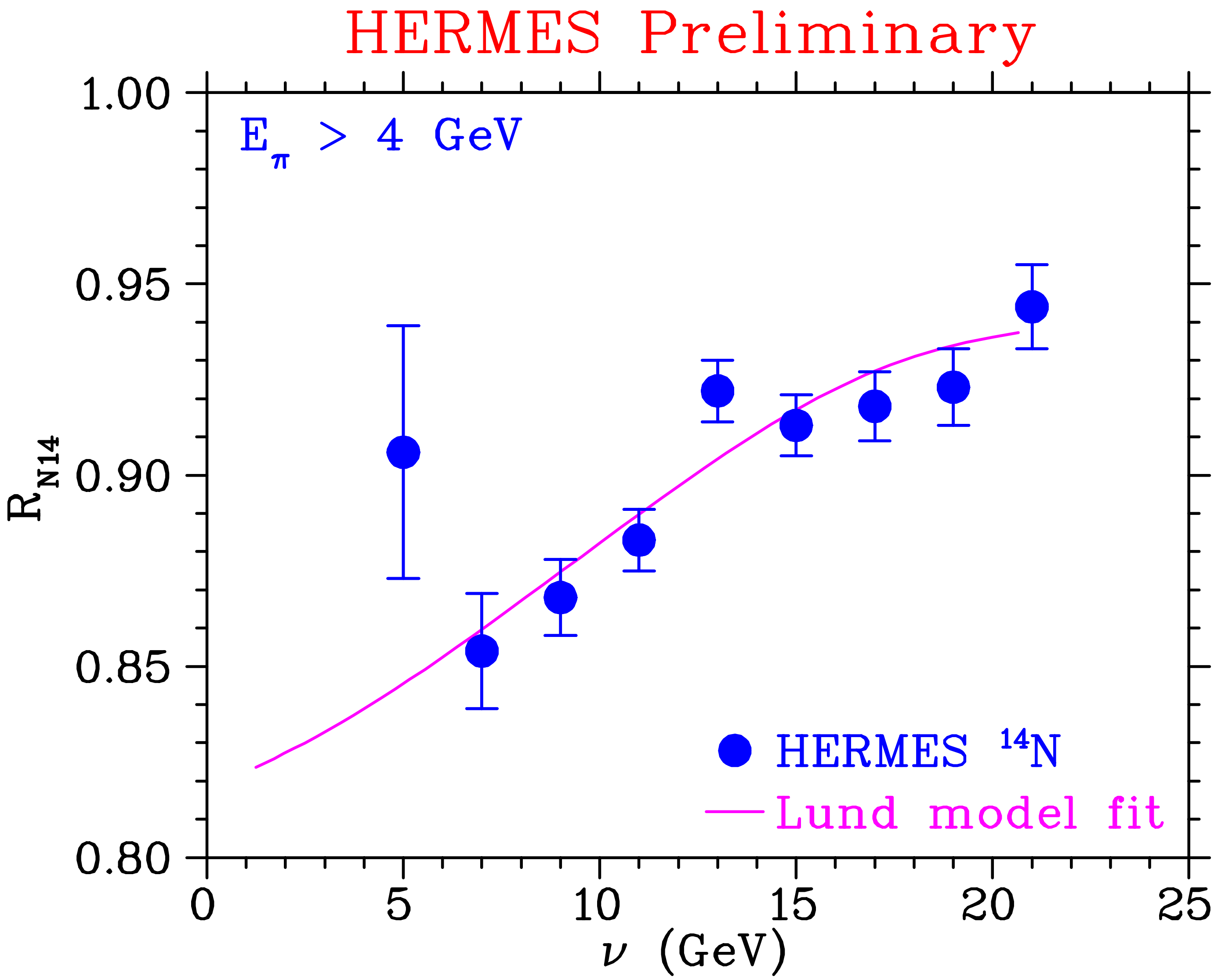


R_A = probability of no interactions using cross sections:



- In gluon bremsstrahlung model, fragmentation at large Q^2 through perturbative $q \to qg$ and $g \to q\bar{q}$ [B. Kopeliovich, J. Nemchik and E. Predazzi, Nikhef 96-026, p. 14]
  - Large $\nu \Rightarrow$ color transparency $\Rightarrow R_A \sim 1$
    - large z, $Q^2 \Rightarrow$ hadron formed with small $r_\perp$
    - small size $\Rightarrow$ reduced nuclear interactions
    - large $\nu \Rightarrow$ wavepacket frozen in small configuration
  - Parameter-free postdiction

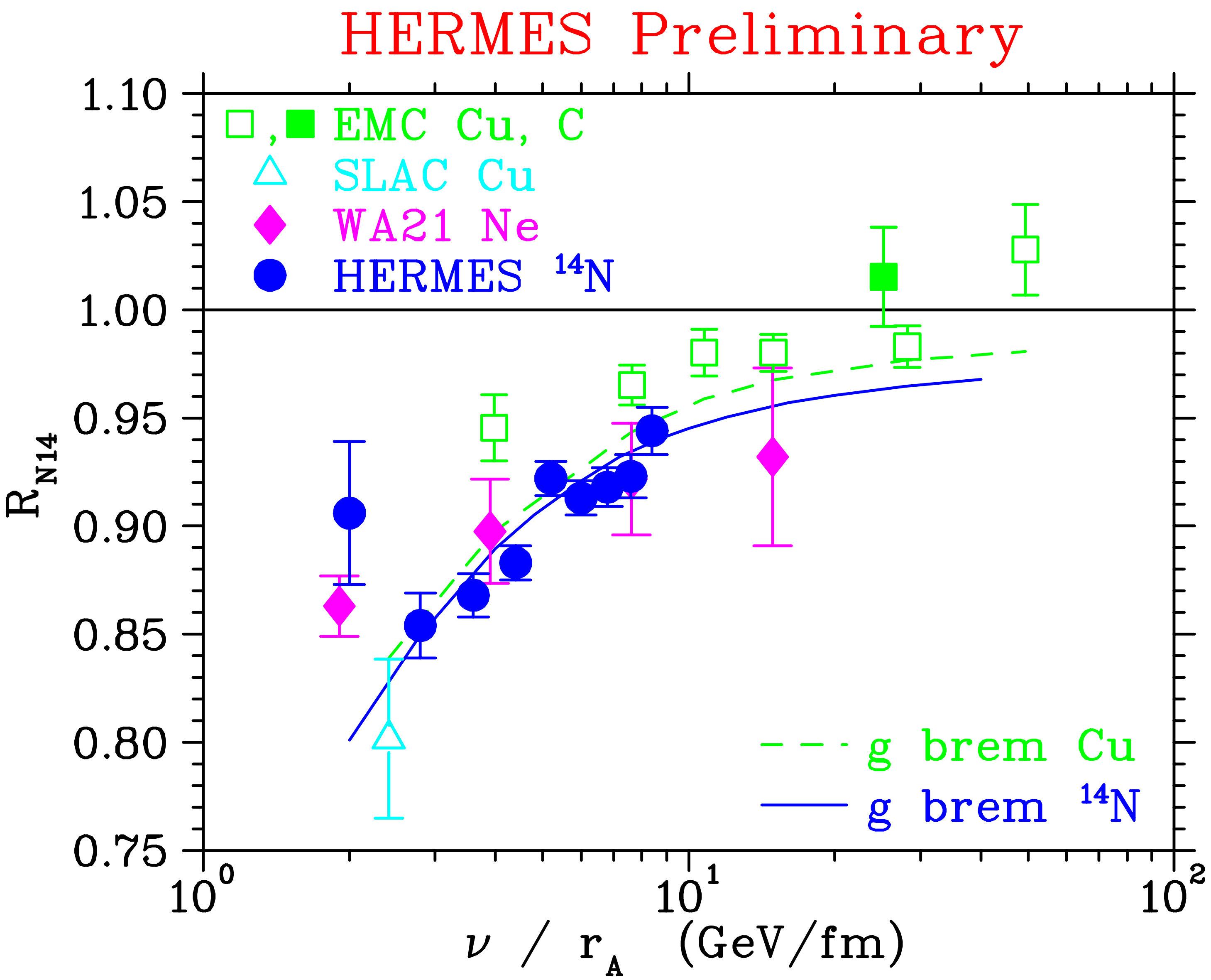
Hadronization in Nitrogen



- HERMES ^{2}H and ^{14}N $eN \to e\pi^\pm Y$, $E = 27.5$ GeV.
- Preliminary result of J. van Hunen; continuing analysis also by P. di Nezza and V. Muccifora.
- z_h up to 0.95 (previously: $z_h \leq 0.8$)

cut	explanation
$1 < Q^2 < 19\,\mathrm{GeV}^2$, $4 < W^2 < 45$ GeV^2	DIS
$y = \frac{P\cdot q}{P\cdot k} = \nu/E < 0.85$	suppress radiation
$0.04 < x < 0.8$	suppress shadowing
$E_\pi > 4$ GeV $[z_h > (4\text{ GeV}/\nu)]$	Čerenkov threshold

World Data on Hadronization



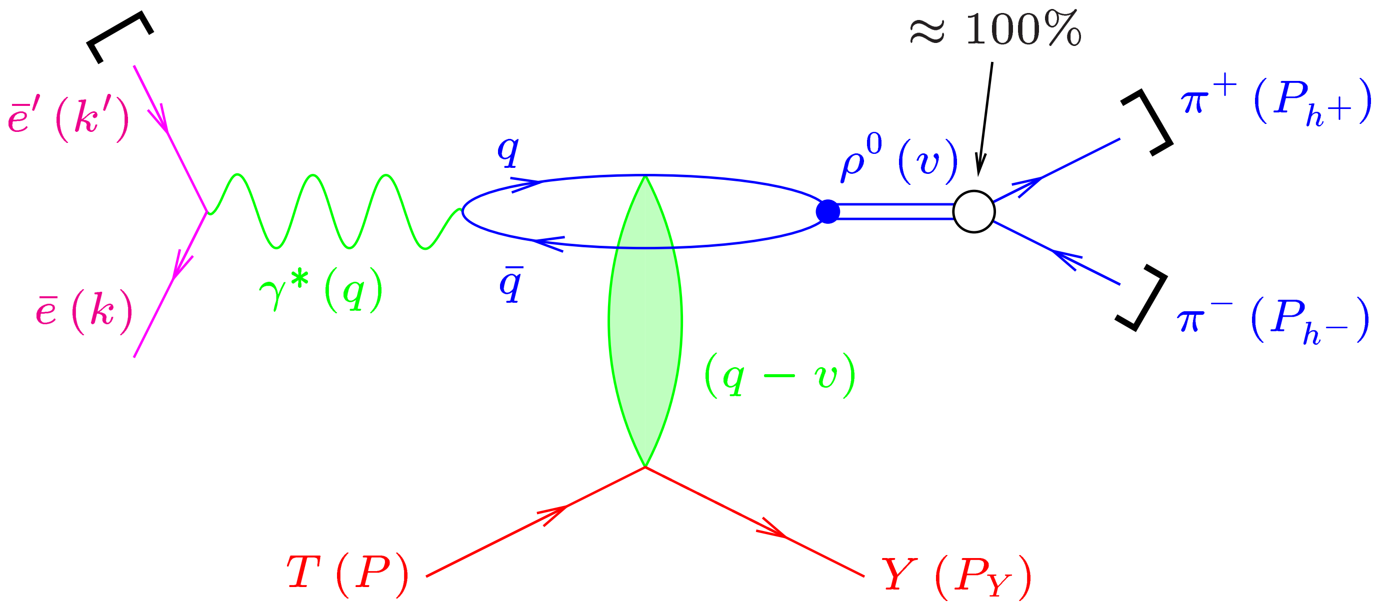
- $\nu/r_A \propto l_f/r_A$ (e.g., $l_f = \nu\tau_f/m_q$)
- Assume $R_A = (A/2)^{\alpha(\nu/r_A)}$ for each datum, plot for $A = 14$
- CERN WA21/WA59 ^{1}H, Ne $\nu N \to \mu^- h^\pm Y$ and $\bar{\nu} N \to \mu^- h^\pm Y$ [W. Burkot *et al.*, Z. Phys. C **70** (1996) 47]
- Gluon bremsstrahlung model [B. Kopeliovich, J. Nemchik and E. Predazzi, Nikhef 96-026, p. 14]
- HERMES (others): $\pi^\pm$ ($h^\pm$) at $z_h > 4$ GeV$/\nu$ ($z_h > 0.2$)

HERMES ρ^0 Electroproduction Signal

ρ^0, $\rho^\pm$ have $I(J^{PC}) = 1(1^{--})$ [N.B.: γ has $0, 1(1^{--})$]

- $M_\rho = 770$ MeV, $\Gamma_\rho = 150$ MeV ($c\tau = 1.3$ fm)
- ρ^0 content is $(u\bar{u} - d\bar{d})/\sqrt{2}$

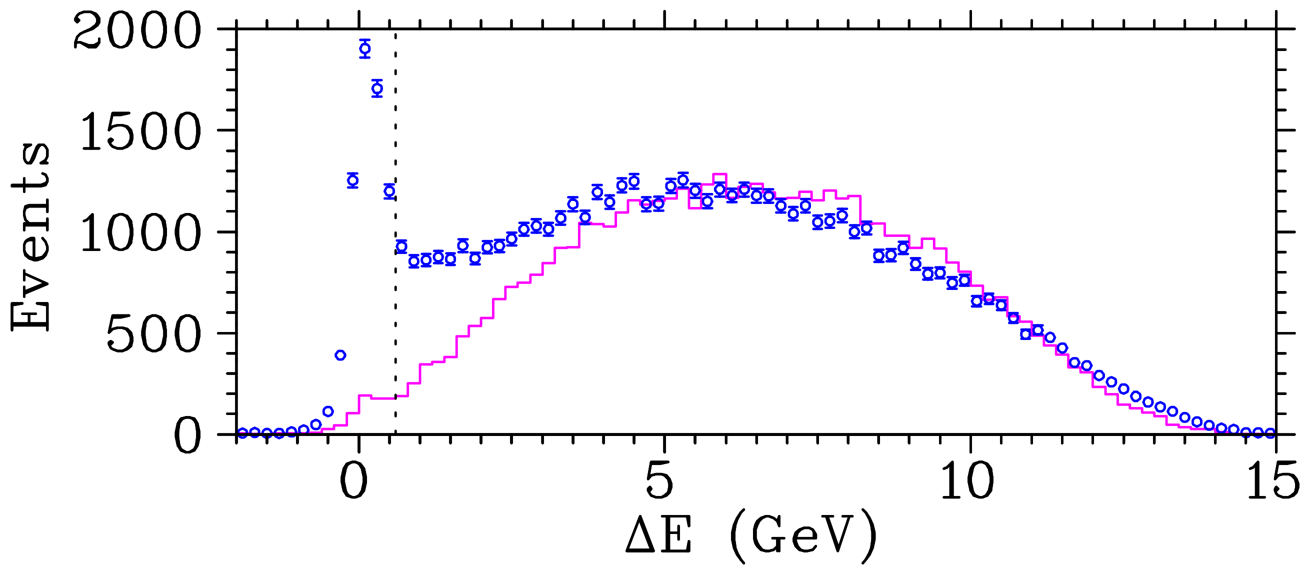
Dominant time-ordered diagram (lab frame):

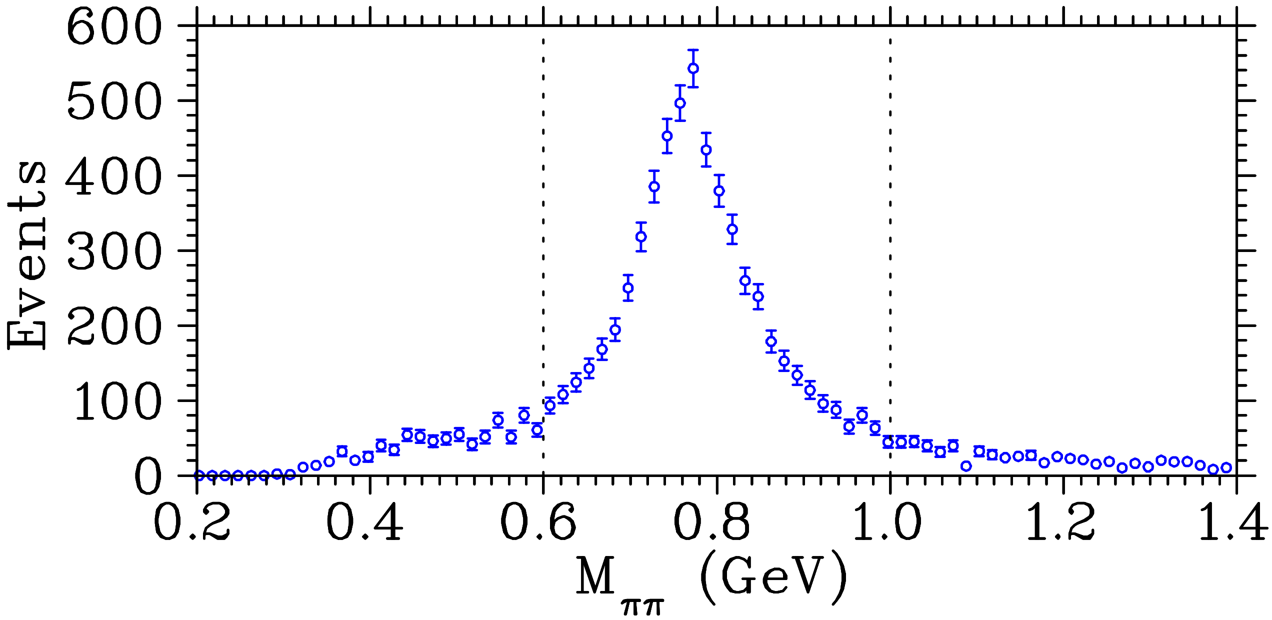


- Exclusive: $M_Y = M_T$
- Diffractive: $d\sigma/dt \sim e^{bt}$ (note $t < 0$)
  - Incoherent: $\gamma^* N \to \rho^0 N$, $b_N \approx 7\ \mathrm{GeV}^{-2}$ (for $A > 1$, this is nuclear inelastic)
  - For $A > 1$, coherent: $\gamma^* A \to \rho^0 A$, $b_{^{14}\mathrm{N}} \approx 55\ \mathrm{GeV}^{-2}$

Selecting Exclusive $eN \to e\rho^0 N$

Events at $0.1 < -t' < 0.4$ GeV^2:





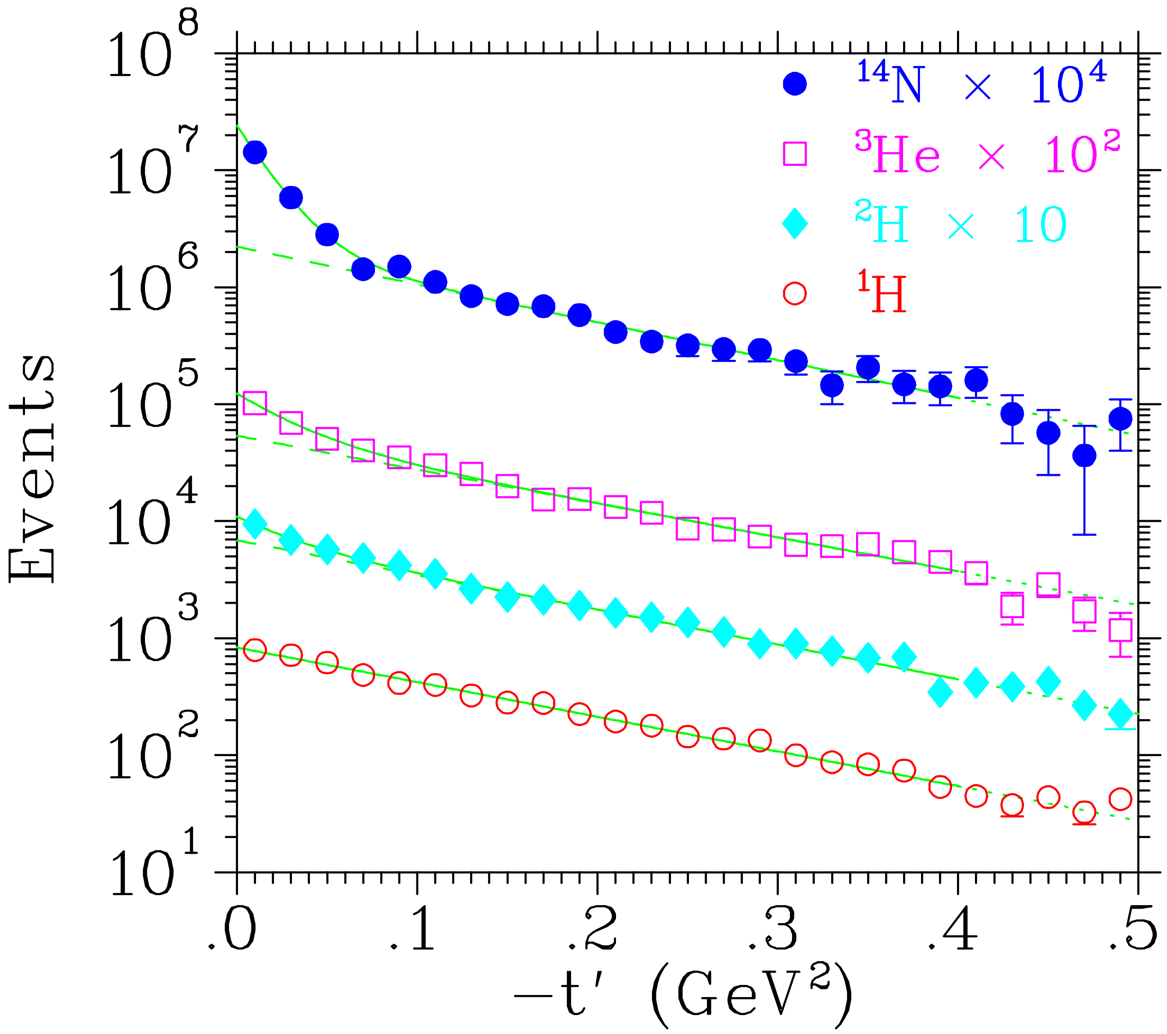
- $\Delta E \equiv (M_Y^2 - M^2)/2M = \nu - E_{\pi\pi} + t/2M$
  - $0.6 < M_{\pi\pi} < 1$ GeV
  - shape of DIS background from $0.7 < -t' < 5$ GeV^2 data
  - also: diffr. ρ^0 plus brem photon or N dissociation

- $M_{\pi\pi}^2 \equiv v^2 = (P_{h^+} + P_{h^-})^2$
  - $\Delta E < 0.6$ GeV, background-subtracted
  - $M_{KK} > 1.04$ GeV
  - also: resonant ω, non-resonant $\pi^+\pi^-$

Selecting Exclusive, Diffractive ρ^0 Production

$$t \equiv (q-v)^2 = (P-P_Y)^2 < 0; \qquad t_0 \equiv t(\theta^{CM}_{\gamma\rho} = 0)\Big|_{(Q^2,\nu,M_Y,M_{\pi\pi})\ \mathrm{fixed}}$$

$$t' \equiv t - t_0 \sim v_t^2$$



Approx. b_A (GeV)$^{-2}$	r_A (fm)
55	2.5
30	1.9
40	2.1
7	0.8

$$\frac{dN}{dt'} = a_N(b_N e^{b_N t'} + f_A b_A e^{b_A t'})$$

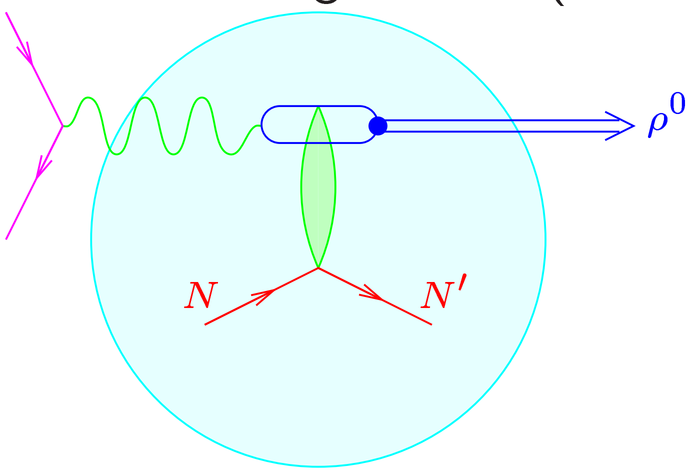
- Incoherent: $b_N \approx 7\ \mathrm{GeV}^{-2}$
- $b \approx \frac{1}{3}\left[\langle R^2_{\mathrm{targ}}\rangle + \langle R^2_\rho\rangle\right]$ (e^{bt} represents elastic F.F., squared)
- Cut: $t'_l(l_c) < -t' < 0.4\ \mathrm{GeV}^2$
  - $t'_l(l_c)$ chosen so $f_{\mathrm{coh}}(l_c) < 1.05$, $\Delta f_{\mathrm{coh}}(l_c) < 0.04$
  - $t'_l(l_c)$: 0.03–$0.05\ \mathrm{GeV}^2$ (^{2}H), 0.03–$0.14\ \mathrm{GeV}^2$ (^{3}He), 0.05–$0.09\ \mathrm{GeV}^2$ (^{14}N)

Coherence Length Dependence of ISI

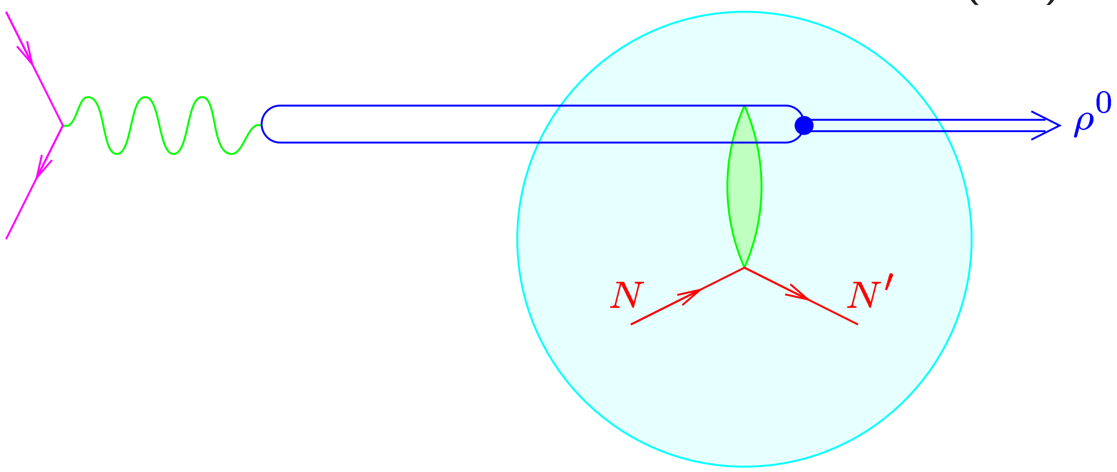
- Heisenberg $\Rightarrow$ lifetime of $q\bar{q}$ pair ($\hbar = 1$):

$$\Delta E_{q\bar{q}} = E_{q\bar{q}} - \nu = \sqrt{M_{q\bar{q}}^2 + (Q^2 + \nu^2)} - \nu$$
$$\underset{\nu \gg Q, M_{q\bar{q}}}{\approx} \frac{M_{q\bar{q}}^2 + Q^2}{2\nu}$$
$$l_c \equiv \frac{2\nu}{M_{q\bar{q}}^2 + Q^2} \quad \left(\approx \frac{1}{\Delta E_{q\bar{q}}}\right)$$

- Strength of the ISI depend on l_c [K. Gottfried and D.R. Yennie, Phys. Rev. **182**, 1595 (1969)].
  - $l_c \ll r_A \Rightarrow$ weak electromagnetic ISI (naive expectation):

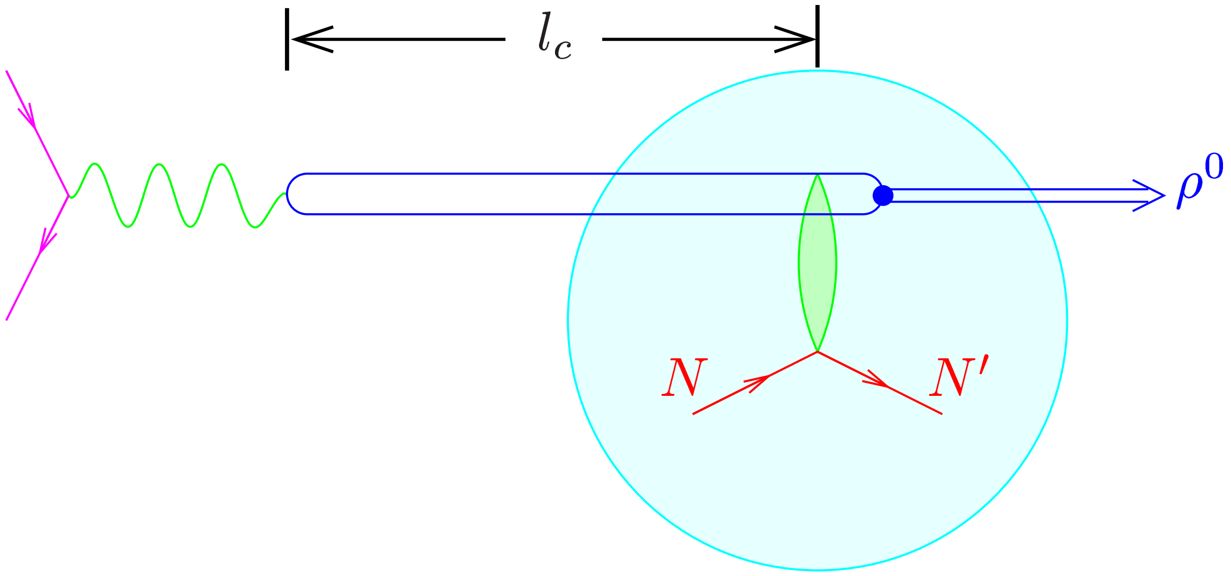


  - $l_c \gg r_A \Rightarrow$ hadronic Initial State Interactions (ISI):



  - $q_{\|} - P_{q\bar{q},\|} \approx 1/l_c \Rightarrow$ phase for ρ^0 production at z is e^{iz/l_c}

Incoherent Nuclear Transparency T_A



- Without ISI and FSI, incoherent $\sigma_A = A\sigma_N$
- Incoherent nuclear transparency: $T_A \equiv \sigma_A / A\sigma_N$
  - Effect of ISI of γ^*, $q\bar{q}$ and FSI of ρ^0
  - Factorization $\Rightarrow T_A =$probability of transmitting $\gamma^*/q\bar{q}$ and ρ^0 unscathed
- T_A should decrease with onset of hadronic ISI at $l_c \gtrsim 1$ fm (note $\sigma_{\rho N} \approx$ constant for $\nu > 1$ GeV)

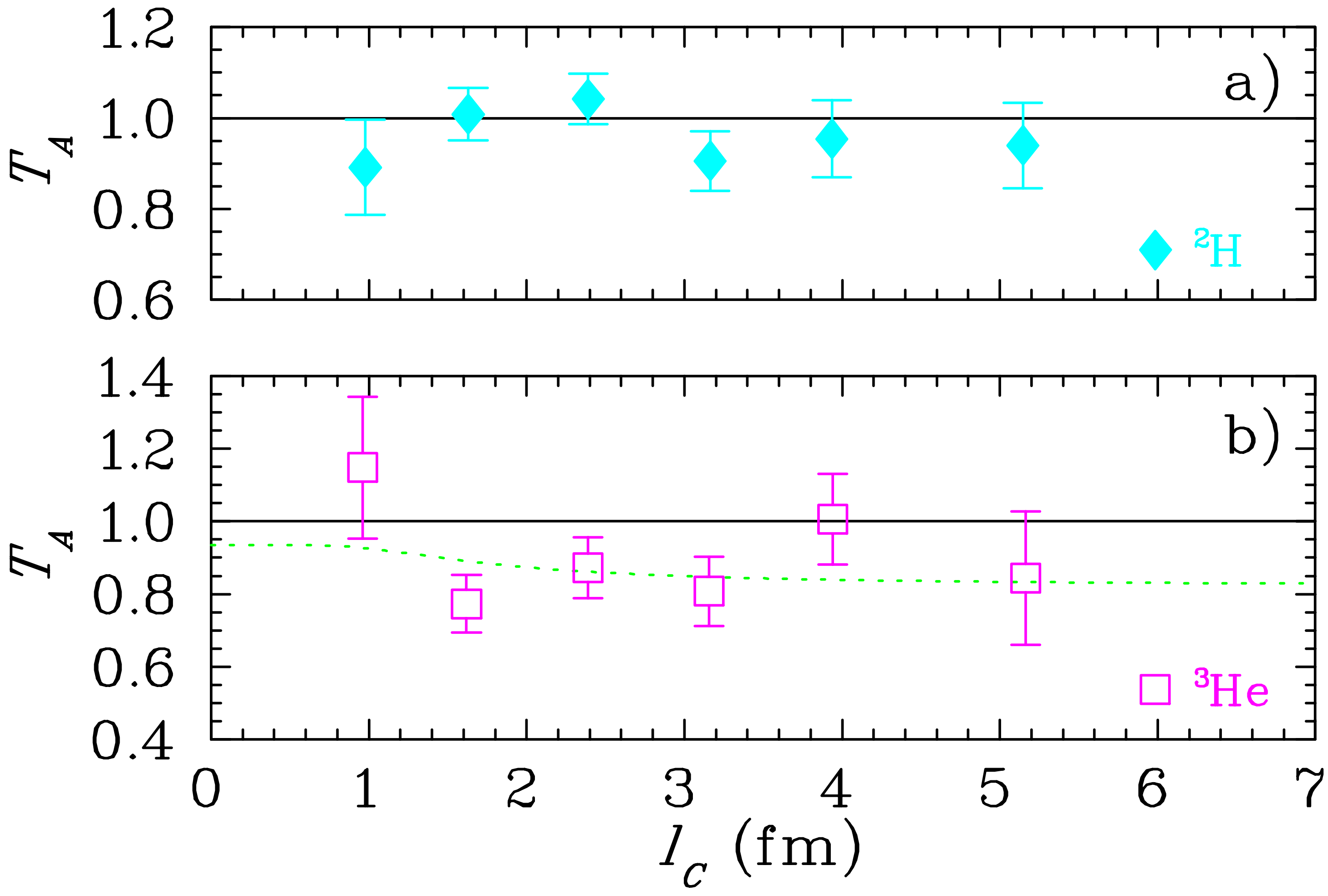
- Expect $\sigma_n \approx \sigma_H \Rightarrow$ use $\sigma_N = \sigma_H$:

$$T_A \equiv \frac{\sigma_A}{A\sigma_H} = \frac{N_A L_H}{A N_H L_A}$$

- L_A from DIS $eN \to eX$, reduced by h^+h^- efficiency
- $N_{A,H} = \#$ of incoherent events at $t'_l < -t' < 0.4$ GeV^2 $(N_A = N_A^{\rm tot}/f_{\rm coh})$
- t'_l chosen so that $f_{\rm coh} < 1.05$, $\Delta f_{\rm coh} < 0.04$

Nuclear Transparency $T_{^2\mathrm{H}}$, $T_{^3\mathrm{He}}$

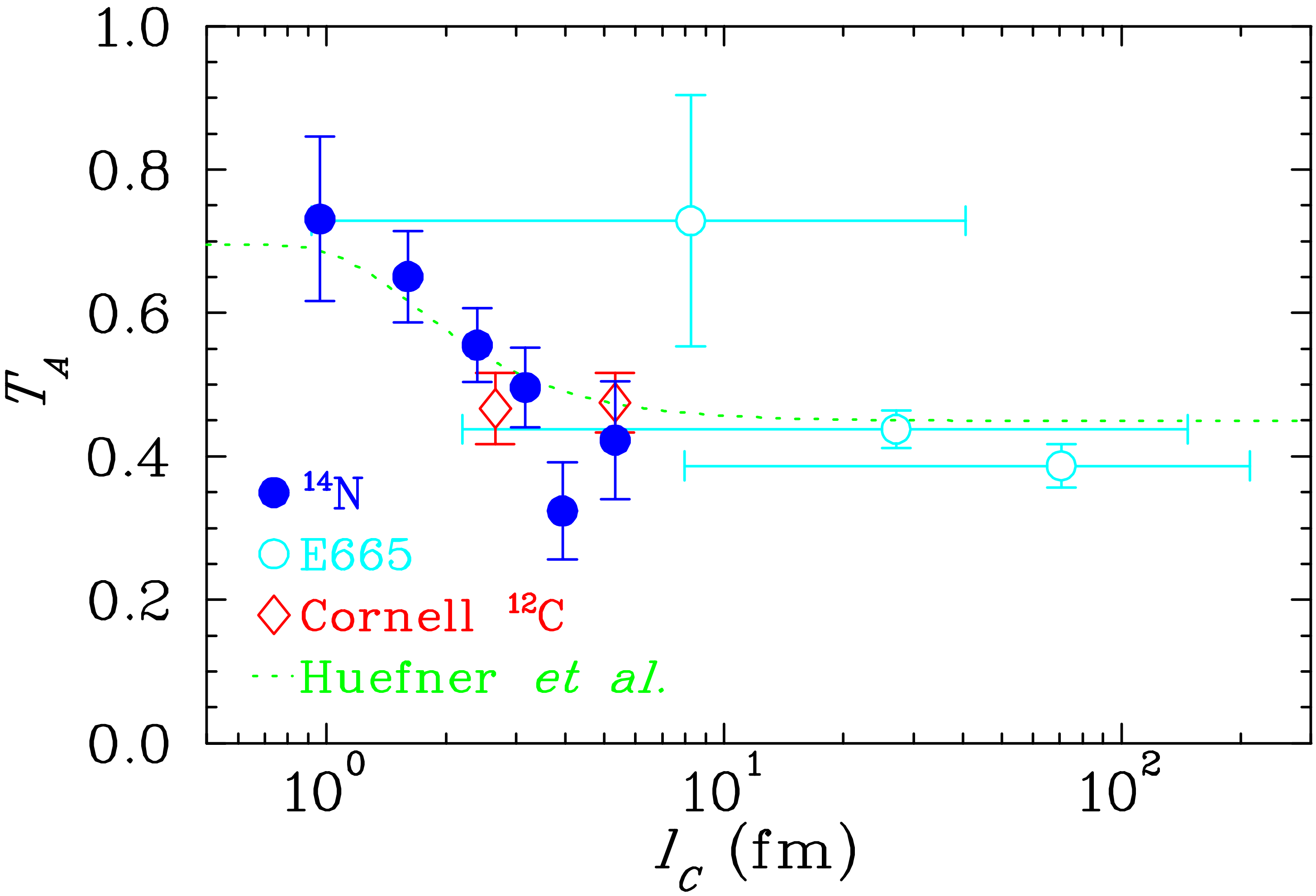
[K. Ackerstaff *et al.* (HERMES collaboration), Phys. Rev. Lett. 82 (1999) 3025]



- Systematic uncertainty:
  - fit uncertainty Δf_{coh} in f_{coh}
  - background subtraction procedure
  - time dependences
  - Point-to-point systematic uncertainty added in quadrature
  - 2.7% (5.5%) uncertainty in $\langle T_{^2\mathrm{H}}\rangle$ ($\langle T_{^3\mathrm{He}}\rangle$) not shown
- suggests $\sigma_n \approx \sigma_H$ and small ISI/FSI in ^{2}H

Coherence Length Effect in $T_{^{14}N}$

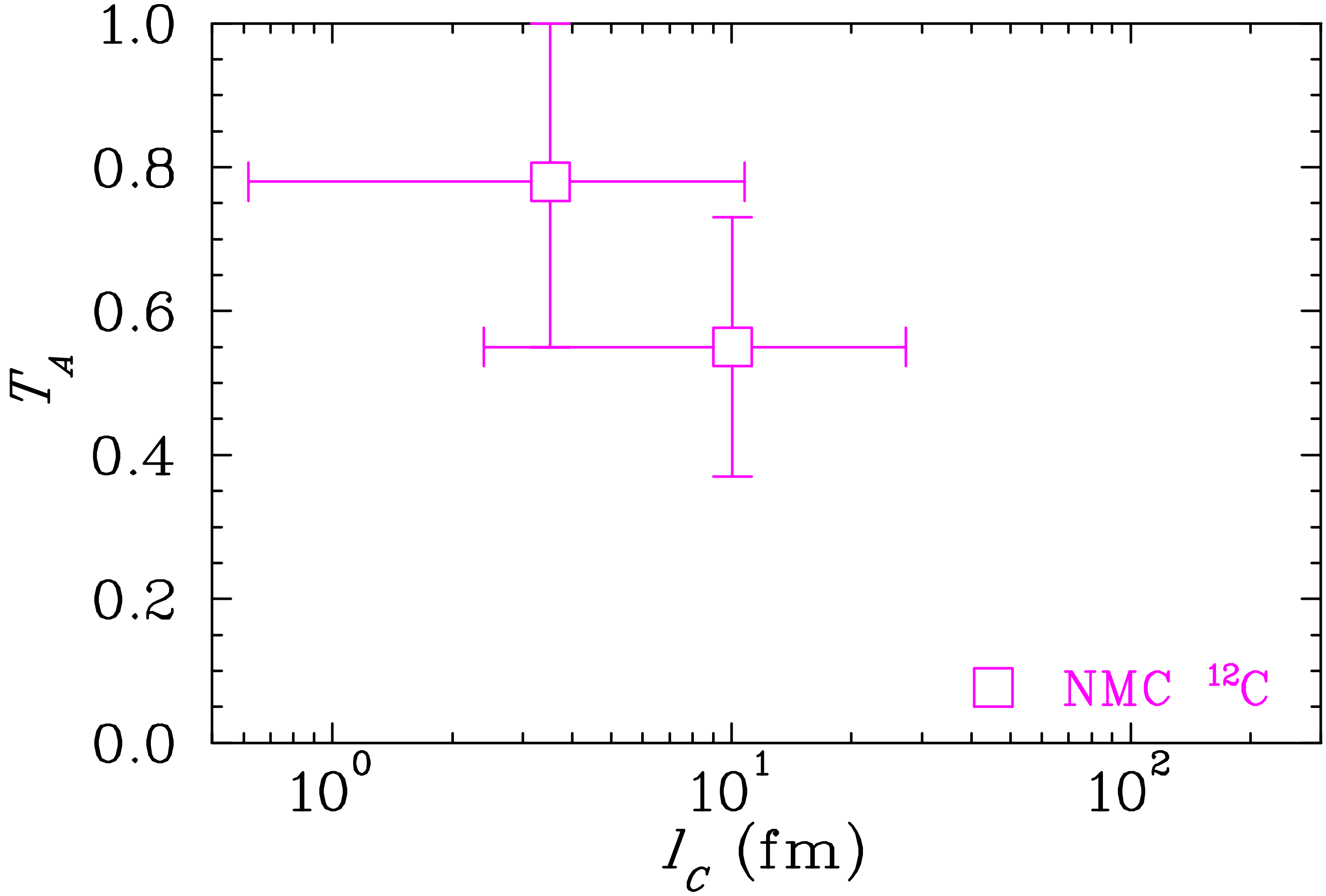
[K. Ackerstaff *et al.* (HERMES collaboration), Phys. Rev. Lett. 82 (1999) 3025]



- 5.9% uncertainty in HERMES $\langle T_{^{14}N} \rangle$ not shown
- Cornell: $\gamma N \to \rho^0 N$, $E = 4$, 8 GeV [G.N. McClellan *et al.*, PRL **23** (1969) 554]
- FNAL E665: $\mu N \to \mu \rho^0 N$, $E = 470$ GeV [M.R. Adams *et al.*, PRL **74** (1994) 1525]
- CERN NMC: $\mu N \to \mu \rho^0 N$, $E = 200$ GeV [M. Arneodo *et al.*, NPB 429 (1994) 503]
- Glauber prediction [J. Hüfner, B. Kopeliovich, J. Nemchik, PLB **383** (1996) 362]

hermes

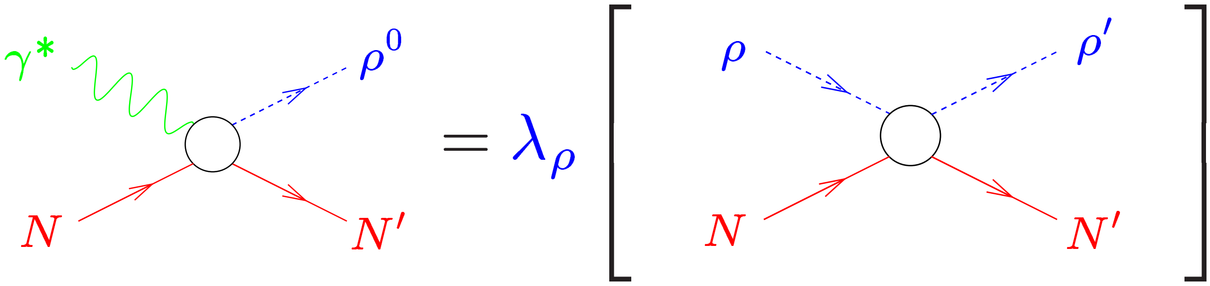
Nuclear Transparency $T_{^{14}\mathrm{N}}$



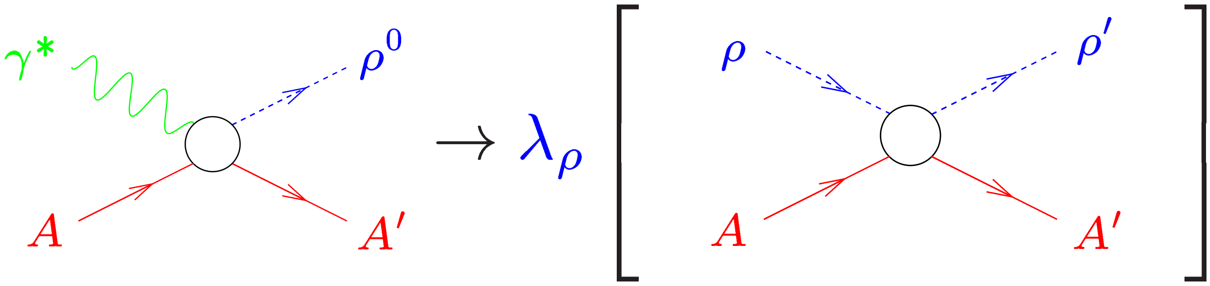
Prediction for Coherence Length Dependence

[J. Hüfner, B. Kopeliovich, J. Nemchik, PLB **383** (1996) 362]

- Glauber multiple-scattering (diffraction) theory



- Phase for ρ^0 production at long. position z is e^{iz/l_c}
- At $l_c \gg r_A$, equivalent to $\gamma \to \rho^0$ before entering nucleus:



- Agreement with data at low, high $l_c \Rightarrow$
  - Lifetime of $q\bar{q}$ correctly given by l_c
  - For $l_c \gg r_A$, $\sigma_{q\bar{q},N} \approx \sigma_{\rho N}$
- Similar calculation can explain DIS shadowing data ($x \approx 1/Ml_c$) [*e.g.*, G. Piller and W. Weise, PRC **42** (1990) R1834]; note $\Delta T_A(l_c) >$ shadowing

Conclusions

- Nucleus used to probe lifetime and interactions of virtual states
- Hadronization in DIS: virtual quark or color string
  - Interaction smaller before hadron's first constituent appears
  - Q^2, z_h dependences (more stats?) $\Rightarrow$ test models
- Exclusive ρ^0 production: virtual $\gamma^* \rightarrow q\bar{q}$
  - Lifetime given by Heisenberg assuming $M_{q\bar{q}} = M_\rho$
  - Interacts like a ρ^0
- HERMES greatly improves world data for hadronization, ρ^0
- Plus: more HERMES data to come!
  - 1998: Čerenkov $\rightarrow$ RICH
    - $K^\pm$, $p/\bar{p}$ ID
    - $\pi^\pm$ down to 1 GeV/c
  - Krypton in 1999